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Stump harvesting in *Picea abies* stands: Soil surface disturbance and biomass distribution of the harvested stumps and roots

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ABSTRACT

Finland has a long tradition of utilizing forest-based biomass for energy and industry purposes and the use has steadily increased in the past decade due to changes in international and regional energy policies. Intensive harvesting practices, in which a larger proportion of the woody biomass is removed from the forest stand, are becoming more common. The objectives of this study were (i) to evaluate the spatial and temporal extent of soil surface disturbance caused by stump-root system harvesting and (ii) to quantify how much biomass and nitrogen is removed from the stand in stump and coarse root harvesting. The extent of surface disturbance was assessed in three clear-cut Norway spruce (*Picea abies*, (L.) Karst.) stands in southern and central Finland, differing in time since harvest. To determine the biomass distribution of the stump-root system, stumps and coarse roots were excavated at one of the experimental stands.

Across all age classes (time since harvest) less soil surface had remained undisturbed at the stump harvesting sites (52%) than at the sites where only mechanical site preparation (28%) had been carried out. Thus, the findings of this study indicate that soil disturbance caused by stump harvesting can exist on forest soil surface for more than a decade following harvest. The total biomass of the stump-root system in the stand was estimated to 39.3 Mg ha^{-1} and 79% of this biomass was removed during stump harvesting and consequently, 8.3 Mg ha^{-1} of stump-root biomass remained in soil. The stump-root system accounted for 17% of the whole-tree biomass, and coarse roots and fine coarse roots represented a significant portion of it (73%). Thus, the stump-root system represents a large biomass component in boreal forest stands. However, forest management utilizing stumps may result in carbon losses from the stand.

1. Introduction

There is an increasing interest for using renewable sources to replace a part of the fossil fuels in energy production in the European Union. In Finland, like in many forested countries, forest bioenergy is considered a sustainable and easily accessible energy resource. The use of wood-fuels has steadily increased within the last century, with the current share of wood-based fuels (this includes forest biomass and industrial by-products such as saw dust and black liquor) being 75% (in 2017) of renewable energy consumption and 26% of the total energy consumption (19.5 million m^3 – increase of 6% from 2015; LUKE, 2017). Forest bioenergy includes logging residues, stumps and small-size or inferior-quality tree stems that are normally not harvested in conventional, stem-only harvesting (Helmisaari et al., 2014). In Finland, stump harvesting started in 2000 and peaked in 2010–2013 with 1.1 million m^3, the current annual harvest being 0.76 million m^3 (LUKE, 2017). In practice, stump harvesting is currently predominantly carried out in fertile and moderately fertile Norway spruce (*Picea abies* (L.) Karst.) stands.

The effects of forest bioenergy harvesting on forest soil and tree growth have been shown to be site-, soil- and practice-specific (Walmsley and Godbold, 2009; Thiffault et al., 2011; Strömgren et al., 2013; Egnell, 2016). Stump harvesting is often combined with logging residue harvesting, after which the soil is prepared mechanically for the planting of the next tree generation. Mounding is the most common method used in Finland for planting Norway spruce (Kortesmaa et al., 2017). These procedures combined are more likely to cause greater direct effects on forest soil structure and indirect effects on soil

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processes, such as on the biogeochemical cycles, than either of these practices alone. Studies conducted in Finland have reported soil mixing and redistribution of soil organic matter (SOM) within the soil profile during 1–5 years (Kataja-aho et al., 2012) and 11–12 years (Kaarakka et al., 2016) after stump harvesting. A recent study by Persson et al. (2017) showed a tendency for changes in surface soil carbon (C) pools (organic layer + 0–10 cm mineral soil) 20–30 years after stump harvesting when compared to mounding, but observed no effect on soil C mineralization rate or soil nitrogen (N) transformations or pools.

Karlsson and Tamminen (2013) found no treatment effect on soil C and N pools 30 years after stump harvesting, whereas they reported an increase in tree seedling growth and natural regeneration. Stump harvesting causes heavy traffic at the logging site, as logging equipment is hauled to and from the stand, thus potentially resulting in more soil disturbance. Berg et al. (2015) reported a disturbed area of on average 6 m^2 per harvested stump. Bigger stumps come with an added yield from a bioenergy perspective, however, the average soil area disturbed increases exponentially with increasing stump size (Berg et al., 2015). Previous studies have reported that stump harvesting exposes a large surface area of mineral soil thus resulting in a larger area disturbed compared to site preparation (Kataja-aho et al., 2011a, 2012; Strömgren and Mjöfors, 2012; Saksa, 2013; Tarvainen et al., 2015). Stump harvesting also inevitably reduces the remaining stump and root biomass in the stand (Eräjää et al., 2010; Hyvönen et al., 2016).

Carbon neutrality of intensified forest biomass harvesting has been questioned in recent research (Repo et al., 2011; Schulze et al., 2012; Zanchi et al., 2012; Repo et al., 2015). Forest biomass removal results in direct and instant (i.e. combustion), as well as indirect and delayed C emissions (i.e. loss of decomposing biomass) from the harvested stand. In other words, carbon allocated to woody biomass will be released immediately instead of being retained in the ecosystem. Thus, the choice of the forest biomass partitioning used for bioenergy purposes greatly affects the magnitude and timing of potential C losses (Repo et al., 2011, 2012, 2015). Northern temperate and boreal forests are characterized by long stand rotation times (over 70 years) and relatively slow tree growth, which is in part limited by low N availability on mineral soils (Högberg et al., 2017). Stump and large diameter coarse roots are the largest coarse woody debris (CWD) component in a managed boreal forest, as other types of CWD are extracted in forestry operations (Eräjää et al., 2010; Palviainen et al., 2010; Rabinowitch-Jokinen and Vanha-Majamaa, 2010). Stumps and coarse roots decompose slowly, thus in a managed forest stand they serve as long-term C and N pools and as sources of nutrients (Melin et al., 2009; Hellsten et al., 2013; Palviainen and Finér, 2015). Therefore including stump-root systems in soil C and nutrient budgets of the whole stand would greatly improve the accuracy of these budgets/estimates (Sucre and Fox, 2009). Stump harvesting equivalents root harvesting as coarse roots and fine coarse roots represent the largest fraction removed in stump harvesting (Hyvönen et al., 2016). In the context of this article, stump-root system refers to the stump, coarse roots (diameter > 35 mm) and fine coarse roots (diameter = 5–35 mm) (Fig. 1).

Only a handful of studies have attempted to estimate the biomass and N removals associated with stump and coarse root removal (Hakkila, 1975; Augusto et al., 2015; Palviainen and Finér, 2015) due to the arduous nature of sampling entire stump-root systems. In Finland, a biomass study compiled from data from over 400 conifer stump-root systems estimated that stumps and coarse roots (diameter ≥ 5 cm) comprised 26–34% and 68% of the entire stump-root system biomass in a mature Norway spruce stand, respectively (Hakkila, 1975).

In Norway spruce roots, wood density increases from stump to roots, as the growth near the stump is faster and growth rings are thus larger (Hakkila, 1975). Harvested woody biomass also almost always includes the bark and finer roots which have a higher proportion of bark than coarse roots (Hakkila, 1975). Bark contains more nutrients than root wood (Hellsten et al., 2013), which contributes to thinner coarse roots having a higher concentration of nutrients. Fine, absorptive roots break

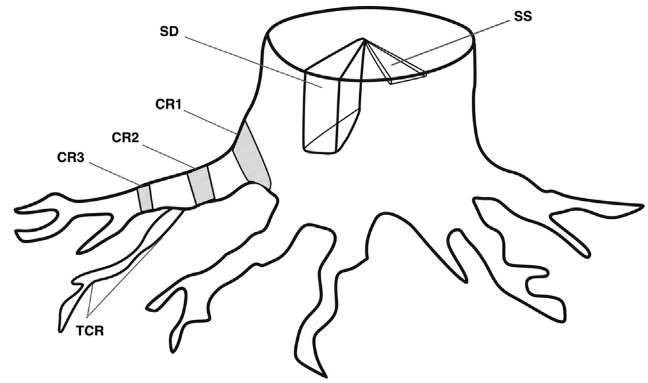

Fig. 1. Illustration of the sampling of the stump-root system. Stump sector (SS) and stump disc (SD) samples were collected in longitudinal and vertical direction, respectively. Coarse root discs (CR1–CR7) (diameter > 35 mm) were collected from the coarse roots in the direction of root in 30 cm intervals. Thin coarse roots (TCR) (diameter = 5–35 mm) were sampled in their entirety (i.e. the whole root was collected). Image is not to scale. Modified from Vaittinen, 2008.

easily at stump harvesting and therefore a part of them remains in the soil after harvesting. Nevertheless, if fine roots are removed with the stumps a substantial nutrient loss is likely (Hellsten et al., 2013) which in turn may potentially contribute to a growth loss in the next tree generation (Weatherall et al., 2006).

The aim of this study was to estimate the extent of soil surface disturbance caused by stump harvesting and how much biomass is removed from a stand in stump harvesting. More specifically, we wanted to quantify how much C and N is removed from the soil with the stumps and coarse roots that are pulled along with the main stump and assess the long-term impacts of stumps harvesting on soil C and N pools. Finally, we wanted to assess whether the disturbance effects of stump harvesting on soil surface persist over time.

2. Materials and methods

2.1. Experimental design

2.1.1. Soil surface disturbance

Three clear-cut Norway spruce sites (site is synonomous to stand in the context of this experiment), located in central and southern Finland, were studied. All the sites were located in the boreal vegetation zone, in the humid continental region (Table 1). The sites differed in time since harvesting: Haukilahti was clear-cut in 2001, Karkkila in 2007 and Hyvinkää in 2010. In 2014, 4, 7 and 13 years after final harvesting, six (5 m × 5 m, 25 m^2) experimental plots were established at each experimental site; three plots where mounding was carried out and three where stumps had been harvested in addition to mounding. Altogether 18 experimental plots were established (n = 3 per site). Experimental plots were located at a distance of at least five meters from other experimental plots and the edges of the whole site. Stony boulder areas and major forest machine paths were avoided and due to the lack of visible tracks on the experimental plots, wheel ruts were not included in the disturbance classification. The experimental plots were located in a 4 × 4 km area in Haukilahti and 300–600 m apart in Hyvinkää and Karkkila. Each 25 m^2 experimental plot was further divided into 25 separate one square meter frames, in which the soil disturbance class was determined using a 24 mm cylinder soil corer. Three disturbance classes were identified: (i) undisturbed, (ii) mound created in site preparation and (iii) excavation/stump pit (Table 2). The percent cover of each disturbance class (%) was estimated within each one meter frame (totaling to 100%).

All the experimental sites had been planted with Norway spruce seedlings the year following clear-cutting.

Table 1
Characteristics of the experimental sites. Annual mean temperature and precipitation is given for 1981–2010 (Pirinen et al., 2012). Effective temperature sum (degree days, d.d.) is the sum of daily mean temperatures above +5 °C for 1961–2016 (FMI, 2018). Forest site types follow the classification system by Cajander (1949).

Location	Haukilahti	Karkkila	Hyvinkää
Coordinates	61°48′N, 24°46′E	60°35′N, 24°13′E	60°38′N, 25°01′E
Year of harvest	2001	2007	2010
Precipitation (mm)	643	647	660
Mean annual temperature, °C	3.8	4.6	4.6
Effective temperature sum, (d.d. above +5 °C)	1191	1350	1350
Harvested stem volume ($m^3 ha^{-1}$) at clear-cutting	270	400	230
Soil type	Sandy loam	Silt loam	Sandy loam
Tree age at clear-cutting	100	77	NA
Forest site type	*Vaccinium myrtillus (MT)*	*Vaccinium myrtillus* (MT)	*Vaccinium myrtillus* (MT)

Table 2
Soil surface disturbance classes and their definitions (modified from Kaarakka et al., 2016; Strömgren and Mjöfors, 2012).

Disturbance class	Definition
Undisturbed	Intact humus layer. No signs of soil surface disturbance nor of mixing between soil layers.
Pit	Humus layer absent. Exposed mineral soil. Vertically lower than the undisturbed soil.
Mound	Exposed mineral soil due to soil inversion with an excavator. Humus layer deeper in the mound. Vertically exposed environment.

2.1.2. Stump and root sampling

One of the sites for soil surface disturbance studies, Karkkila, was the site for biomass sampling, carried out in December 2007. One stump-harvested 30 m × 30 m (900 m^2) experimental plot was used for stump biomass sampling after harvesting. The experimental plot had 33 trees (367 per ha) before clear-cutting. In 2005, two years before clear-cutting stem diameter (1.3 m breast height) and tree heights were determined for 26 trees on the experimental plot. The annual tree growth for 2006–2007 was estimated based on the observed growth in 2000–2005.

In total 26 stump and root systems, including both coarse roots (diameter > 35 mm) and thin coarse roots (diameter = 5–35 mm), were excavated. The diameter and height of each stump was measured before extraction. Each extracted stump was weighed at the field site. In addition, coarse roots and thin coarse roots were separately weighed from 17 trees. During excavation, the stumps were split into smaller chunks and excess soil and rocks were shaken of the stump by the excavator, which is a common practice in stump harvesting.

Stump sector (SS) samples were collected from the stumps in longitudinal direction (Fig. 1). The length/height of these wood samples varied between 30 and 50 cm. In addition, stump disc (SD) samples were collected from the stump. The thicknesses of the stump discs varied between 50 and 60 mm. Coarse root discs (CR) were collected from the coarse roots in the direction of root in 30 cm intervals (diameters 43–62 mm). A few (1–3) of the smaller coarse roots (TCR; diameter 5–35 mm; Hellsten et al. 2013) were sampled in their entirety (i.e. the whole root was collected). All the samples included bark. The samples were sealed in plastic bags and stored in a freezer until further analyses.

2.2. Calculations of stump and coarse root biomass and N stocks

Fresh dry weight and volume for all the stump and root samples, with and without bark, was measured to determine the dry fresh density. The volumes of the wood samples were determined gravimetrically by the water displacement method. The weight of the displaced water represents the volume of the sample, as the density of water is 1 g cm^{-3} (Olesen, 1971).

To determine the dry mass (kg), the samples were dried at 70 °C for 1–5 days, depending on the size of the sample. The biomasses of the sampled stump-root systems were calculated based on the masses of the different fractions (as described above) and summed to obtain total stand stump-root biomass (kg ha^{-1}). The aboveground biomasses for all the trees on the experimental plot were estimated with functions developed by Repola (2009). We used the functions using breast-height diameter and tree height as predictors to estimate the biomass of all aboveground biomass; including bark, stem wood, needles and branches. The aboveground biomasses of individual trees were summed to obtain total stand biomass (kg ha^{-1}). All values used in calculations were dry-weight.

The dry masses for SS, CR and TCR were calculated with the dry substance percentage, which was calculated based on the dry weights of the stump and root samples.

The densities, ρ (g cm^{-3}) of the stump and root samples were calculated with the formula:

$$\rho = m/V, \quad (1)$$

where m = mass of sample (g), V = volume of stump/root sample (cm^{-3}).

The total volumes, V_{tot} (m^{-3}) of the stump, root and aboveground biomass were calculated with the formula:

$$V_{tot} = m/\rho, \quad (2)$$

where m = mass of sample (kg), ρ = density of stump or root wood (kg m^{-3}).

As stump is the lower part of the stem, the mean density value of stump disc (SD) was used as the approximation for stem density. Finally, the volumes of individual trees and stumps and roots were summed to obtain total stand volume ($m^3 ha^{-1}$).

Nitrogen concentrations were analyzed for stump and coarse root wood and bark samples separately using Leco CN-2000 (as described by Hellsten et al., 2013). N concentrations were not determined for fine coarse roots.

2.3. Statistical analyses

Statistical analyses of soil surface disturbances were completed using R, version 3.4.3 (R Core Team, 2018) with two-way ANOVA. Experimental site (time since harvesting), treatment and disturbance class and their interactions were defined as fixed factors. The differences between disturbance classes at each experimental site were analyzed according to a two-way ANOVA, where treatment, disturbance class and their interactions were considered as fixed factors. Differences between treatments were tested using Tukey's post-hoc test. Surface disturbance proportions were log-transformed with a constant of 1 ($\log_{x+1}$) prior to the statistical analyses to meet the requirement of normal distribution and equal variance. Differences were considered statistically significant when $p \leq 0.05$.

3. Results

3.1. Surface disturbance

At all three experimental sites it was evident that more undisturbed surface (70–73%) had remained at the mounded stands, compared to the sites where the stumps had been harvested (40–54%) (Fig. 2).

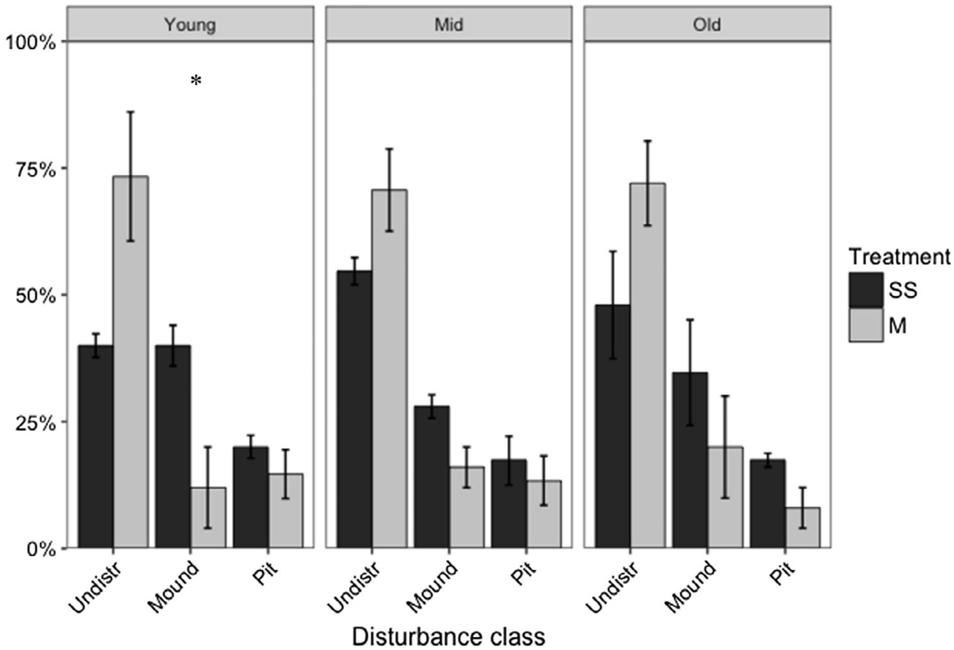

Fig. 2. Proportion of surface disturbance (%) at the Norway spruce stands harvested in 2010 (young – Hyvinkää), 2007 (mid – Karkkila) and 2001 (old – Haukilahti). Two treatments were applied: stump harvesting combined with mounding (SS) and mounding (M) (n = 3). For the description of disturbance classes, see Table 2. An asterisk indicates statistical significance ($p \le 0.05$) for the difference in treatment means of the soil disturbance classes between SS and M.

Neither stump harvesting/treatment nor experimental site (i.e. time since harvesting) were significant factors in explaining the difference in the proportion of different soil disturbance classes. At the youngest site (Hyvinkää), there was a statistically significant difference between stump harvesting + mounding and mounding only. The mound disturbance class covered a larger area at the experimental plots that had been stump harvested and mounded than at the plots with mounding only. Nevertheless, the results give indication that the disturbance effect of stump harvesting can persist in the stand 13 years after the treatment.

3.2. Biomass and N stocks

Wood and bark root density increased with decreasing root diameter (Table 3). In addition, the largest proportion of bark was found in the coarse roots (diameter > 35 mm) furthest away from the stump base.

The total tree biomass of the experimental stand in Karkkila was estimated to 235,561 kg ha^{-1} and this included the stump-root system and total aboveground biomass, including bark, needles and branches (Table 4). The total stump and coarse root biomass at the stand was 39,300 kg ha^{-1} and 79% (30,979 kg ha^{-1}) of this biomass was actually removed during stump harvesting and 21% (8340 kg ha^{-1}) remained in soil. The stump-root system accounted for 17% of the whole-tree biomass. One has to highlight, that this estimate excludes fine-root biomass. Coarse roots represented the largest biomass component in the stump-root system, accounting for 61% of the total biomass and 10% of the whole tree biomass. Stump accounted for 27% of the belowground biomass and 4.5% of the whole tree biomass. The stem is a significant component of the whole tree biomass, and in our study it was estimated to account for 69% of the total tree biomass.

The N stock in the stem and stump-root biomass was estimated to be 202 kg ha^{-1} (Table 5). This excludes needles, branches and fine-roots. The tree stem, including both wood and bark, was the largest N pool at 158 kg ha^{-1}, accounting for 78% of the harvested N. Correspondingly, the stump-root system had a N stock of 44 kg ha^{-1}. Bark accounted for 40%, 27% and 42% of the total N in the stem, stump and coarse roots,

Table 3
Densities of the different stump (SS = stump sector, SD = stump disc) and root wood fractions (CR = coarse root, TCR = thin coarse roots) and their bark. Stump and coarse root harvesting was carried out at Karkkila (see Table 1 for site description).

Stump/root sector	Wood density (incl. bark) kg m^{-3}	Bark volume to wood volume ratio %	Number of samples
SD	360	6.1	13
SS	361	4.6	13
CR 1	398	9.5	15
CR 2	419	10	13
CR 3	429	12	15
CR 4	423	15	12
CR 5	400	16	8
CR 6	409	21	6
CR 7	441	29	2
TCR	452	NA	13

Table 4
Distribution of biomass (kg ha^{-1} dry-weight.) in stumps, coarse roots, fine coarse roots and the stem and the total aboveground tree biomass at Karkkila. Distribution of biomass as percentages are indicated in italic.

	Experimental trees (n = 26)		All trees on plot (n = 33)	
		kg ha^{-1}	kg ha^{-1}	% total tree biomass
Total above-ground[a]		154 614	**196 241**	***83***
Stem[b]		138 980	162 636	*69*
Total stump and roots	% of stump-root system	30 979	**39 319**	***17***
Stump[b]	*27*	8 264	10 489	*4.5*
Coarse roots[b]	*61*	18 896	23 984	*10*
Thin coarse roots[b]	*12*	3 818	4 846	*2.1*
		Total aboveground + stump-root biomass (kg ha^{-1})	**235 561**	

[a] Including bark, needles and branches.
[b] Including wood and bark.

Table 5
Nitrogen (N) pools (kg ha^{-1}) in stumps, coarse roots and the stem at Karkkila. Distribution of N in percentages is indicated in italic.

	Experimental trees (n = 26)	All trees on plot (n = 33)	
	kg ha^{-1}	kg ha^{-1}	% total N to total harvested N
Total stem[a]	**124**	**158**	***78***
Stem wood[a]	75	95	*47*
Stem bark	49	63	*31*
Total stump and coarse roots	**35**	**44**	***22***
Stump wood[2]	4.6	5.9	*2.9*
Stump bark	1.7	2.2	*1.1*
Coarse roots wood[a]	17	21	*11*
Coarse roots bark	12	15	*8*
	Total N harvested, stem and stump + root (kg ha^{-1})	**202**	

[a] Excluding bark.

respectively. Thus bark is a significant pool of N, both in the stem and the stump-root system.

4. Discussion

4.1. Stump harvesting and surface disturbance

The findings of this study are consistent with other studies, which have estimated that more soil surface is disturbed at stump harvesting compared to mounding (Strandstrom, 2006; Kataja-aho et al., 2011b; Strömgren and Mjöfors, 2012; Berg et al., 2015; Tarvainen et al., 2015). In Finland, the proportion of disturbed surface (including both mounds and pits), following stump harvesting has been estimated to 55–90%, whereas 20–30% is estimated to be disturbed following mounding (Strandstrom, 2006; Tarvainen et al., 2015). Correspondingly, Kataja-aho et al. (2011b) reported that 30% of the area remained undisturbed after stump harvesting, but as much as 60% when only mounding was done. The study Kataja-aho et al. (2011b) was done partly in the same region as the oldest site in the present study. In Sweden, Strömgren and Mjöfors (2012) reported that only 25% of the soil surface had remained undisturbed following stump harvesting. Berg et al. (2015) reported surface disturbance of 59–61% post-stump harvesting combined with mounding, but concluded "that much of the ground disturbance is associated with the creation of wheel ruts rather than stump harvest per se." Tarvainen et al. (2015) also reported an increase in soil surface disturbance and exposed mineral soil following stump harvest, but they too acknowledged that some study sites were more heavily disturbed by the logging machinery. In the present study, wheel ruts were not included in the disturbance classification as they were either absent or considered a minor disturbance in the experimental plots. At all the experimental sites, mounding had been carried out immediately after stump harvesting, thus it is possible that wheel ruts had been covered by that treatment. This phenomenon has been observed in other studies assessing the effects of stump harvesting in the Nordic region (e.g. Strömgren and Mjöfors, 2012; Rudolphi and Strengbom, 2016).

To our knowledge, this study is the first to assess the development of harvest-induced soil surface disturbance dynamics across a temporal gradient (i.e. time since stump harvesting). The results of this study indicate that soil disturbance caused by stump harvesting exists for a long period of time. More than half of the soil surface was considered disturbed at the most mature site (logged 13 years ago) following stump harvesting, whereas two thirds were undisturbed at the mounded plots. Because our study sites had similar soil texture, climatic conditions, vegetation and silvicultural methods, the differences resulting from site variation were probably small. Thus it seems evident that stump harvesting combined with mounding causes a greater soil surface disturbance than mounding alone. Nevertheless, heterogeneity of soil extends to its surface. The forest floor is very dynamic in space and time, and the appearance of disturbance changes over time and it becomes harder to identify the different disturbance classes, even with a soil corer. Re-emerging vegetation in part contributes to the changes on the soil surface, adding organic matter into the soils surface. Thus over time, identifying different disturbance classes becomes more challenging and can result in differences between experiments.

4.2. Biomass and N in harvested stumps

In our study, coarse root wood density tended to have an inverse relationship with root diameter; density increased in the finer roots. The variation in wood density along the height of the stem is small (Jyske et al., 2008), as it is dependent on the growth rate of the stem which in Norway spruce is affected by a multitude of factors, including tree phenotype and abiotic factors, such as the growth site and its conditions (Kalliokoski et al., 2008). Anchoring the tree is one of the most important functions of tree roots (Kalliokoski et al., 2008) and most trees produce dense wood at the stem base (i.e. stump) (Hakkila, 1989). However, growth rate tends to be faster in the roots near the stump, resulting in larger radial growth and lower wood density (Hakkila, 1989). Kalliokoski et al. (2008) concluded that root-systems' plasticity results in large variation between tree individuals in terms of root-system size and shape. Furthermore, tree species-specific traits appeared to be more important than the site in determining tree root-system architecture (Kalliokoski et al. 2008). Hakkila (1975) reported a wood density of 452 kg m^3 and 394 kg m^3 for Norway spruce coarse roots and stump wood, respectively, which corresponds to the findings of this study.

In terms of total stand tree biomass, our findings are in-line with other studies from the region. Merilä et al. (2014) estimated that Norway spruce stumps and coarse roots contain 38% and 26% (excluding fine-roots) of the tree biomass in relation to the stem and whole-tree biomass, respectively, in a southern Finnish stand of the same site type (MT; Cajander, 1949). Merilä et al. (2014) too, computed total tree biomasses using Repola's (2009) biomass equations. In another study, also in Finland, Finér et al. (2003) estimated the total stump-root systems biomass (excluding fine-roots) to be 21,875 kg ha^{-1} and total stand tree biomass to be 101,943 kg ha^{-1}, in an old-growth (140 years) Norway spruce stand. Thus the stump-root system accounted for 21% of the total tree biomass. In our study the harvested stump-root systems accounted for 16.7% of total tree (all aboveground + belowground, excluding fine roots) biomass in the stand and coarse roots were the largest biomass component belowground. In a similar experiment in France where the entire stump-root system of maritime pine (*Pinus pinaster*) had been excavated, Augusto et al. (2015) estimated that stumps comprised one fifth of the biomass of the stump-root system. Finally, Merilä et al. (2014) estimated that the stump accounted for 17% and coarse roots for 63% and fine and small roots 22% of the stump-root system (including finer roots, diameter ≤ 5 mm). These findings, together with our study, underline the significance of stumps and coarse roots as a belowground biomass reserve.

The estimates for belowground biomass vary somewhat depending on which part of the fine and small roots are included. In this study coarse roots and thin coarse roots were > 35 mm and 5–35 mm, respectively, in diameter. Using a recent modeling study based on empirical data from sampling sites across Finland, we can estimate the fine root (diameter ≤ 2 mm) biomass to 3300–3600 kg ha^{-1} in a stand corresponding to our experimental stand in terms of tree basal area (Lehtonen et al., 2016), which represents approximately 10% of the total belowground (stump-coarse root-fine root) biomass. Stand basal area has been shown to correlate with fine root biomass in Norway spruce stands, particularly in mature, post-canopy closure stands (Helmisaari et al., 2007; Lehtonen et al., 2016). With fine roots added, the stump-root systems sampled in this study would account for around 18% of the whole-tree biomasses.

Whereas the stump-root system appears to lose a sizeable portion of its biomass in the first 5–10 years following harvest (Grelle et al., 2012; Palviainen and Finér, 2015), both coarse roots and stumps retain N thus serving as long-term storages of N in the soil (Sucre and Fox, 2009; Palviainen et al., 2010; Palviainen and Finér, 2015). Merilä et al. (2014) estimated that the stem (excluding needles and branches) and the stump-root system (excluding the fine-roots) together had a N pool of 262 kg ha^{-1}, out of which 58 kg ha^{-1} was in the stump-root system. Although these values were larger than in our study, the ratio of the pools is the same, i.e. ~20% of N is in the stump-coarse root system. Finér et al. (2003) estimated that the stump and coarse roots had a pool of 94.5 kg N ha^{-1}. However, in their study, the N concentration of small roots (diameter = 2–10 mm) was used as a proxy for coarse root N concentration, which probably resulted in the difference with our findings and in an overestimation of the stump-root system N pool (Finér et al., 2003).

Non-woody fine-roots (diameter ≤ 1 mm) are a significant component in belowground litter input and an important N pool in the soil (Helmisaari et al., 2009). Merilä et al. (2014) estimated that fine and coarse roots (diameter ≤ 5 mm) contain 29% of the tree belowground N. Although fine roots are not purposely harvested during stump harvesting, a proportion of them might be unintentionally pulled with the other roots thus resulting in an greater nutrient removal (Berg et al., 2015).

4.3. Forest management perspective

Stump and coarse roots provide reinforcement of the soil and are therefore important to the bearing capacity of the soil. There is large variation between tree species in terms of stump-root system architecture, stump size and root biomass (Kalliokoski et al., 2008; Vesterdal et al., 2013). Thus it is possible that pulling the stumps of certain species or size classes causes a more penetrative or expansive soil disturbance than others. In practice, bigger stumps are favored during stump harvesting, therefore creating a bias towards smaller stumps being left in the harvested stand (Eräjää et al., 2010).

Based on a modeling study constructed from SOM data from permanent sampling plots of the Finnish National Forest Inventory, Kellomäki et al. (2008) estimated the average organic matter pool in the organic layer to 70,000 kg ha^{-1} at a stand similar to this study. In a boreal coniferous stand the mineral soil too, is a significant pool of C and N (Finér et al., 2003; Merilä et al., 2014). In contrast to coarse roots, a majority of the understory vegetation (grasses, dwarf shrubs) and tree fine roots are in the organic layer or in the first 30 cm of the mineral soil (Helmisaari et al., 2007). Therefore, although stumps and coarse roots contain small amounts of nutrients compared to logging residues and fine roots (Astrup et al., 2018) they potentially have a disproportionate importance in the C and N dynamics deeper in the mineral soil, outside the realm of finer, nutrient rich roots. Thus it is possible that the removal of stump and coarse roots, which penetrate deeper into the mineral soil, therefore contributes to the loss of C from deeper soil layers. Previous studies have indicated that soil mixing caused by stump harvesting does affect the C pool in the organic layer (Persson et al., 2017) and results in the relocation of the SOM in the soil years or decades following harvesting (Mjöfors et al., 2015; Hyvönen et al., 2016; Kaarakka et al., 2016). In a study conducted 25 years after stump harvesting along a climatic gradient in Sweden, Strömgren et al. (2013) found a reduction in the organic layer C stock when stump harvesting was combined with logging residue harvesting, resulting in 6 Mg ha^{-1} difference with conventional, stem-only harvesting.

In practice, stump harvesting is almost always combined with logging residue harvesting (whole-tree harvesting). Merilä et al. (2014) estimated the total tree N pool to 562 kg ha^{-1}, out of which 410 kg ha^{-1} is the needles, branches, stumps and coarse roots. If all tree parts suitable for biofuel purposes are removed with the stem, the resulting N loss from the stand can thus be significant. Following harvesting, N is released rapidly from needles and retained longer in woody parts such as the branches and stumps (Hyvönen et al., 2000; Palviainen et al., 2010; Palviainen and Finér, 2015). Given that C from the finer logging residues (needles, small branches and fine roots) is released during the first years after harvesting (Palviainen et al., 2004, 2010) and the importance of needle biomass as a N stock (Merilä et al., 2014), the removal of logging residues could be delayed or to some extent restricted. In fact, current Finnish forest management guidelines do recommend that 30% of fresh logging residues should be retained following whole-tree harvesting and distributed evenly at the logging site (Äijälä et al. 2010). How well this is translated into practice on a stand level can depend on the skills and time limitations of the forest machine operator (Clarke et al., 2015).

Stumps are one the largest coarse woody debris (CWD) component in a managed boreal forest (Palviainen et al., 2010; Rabinowitch-Jokinen and Vanha-Majamaa, 2010; Palviainen and Finér, 2015). Roots have been assumed to decompose faster than stumps due to their smaller size (i.e. diameter) and higher moisture content, however studies using a chronosequence of different aged Norway spruce stands, have reported that stumps decay significantly faster (Palviainen and Finér, 2015) or at the same rate with the roots (Shorohova et al., 2012). Stump wood and bark decompose at different rates; Shorohova et al. (2012) found no difference between the decomposing rates of the different stump-root fractions (i.e. roots and stumps), but reported a different decay rate for stump wood and bark, with the latter decomposing faster. In a 40-year chronosequence study, Palviainen and Finér (2015) estimated that the average annual rate in which C is released from stumps and coarse roots following clear-cutting is 0.3–0.4 Mg C ha^{-1}, which over a rotation of 65 years results in 19.5–26 Mg C ha^{-1} loss, if stumps are removed. Thus at the experimental stand in Karkkila, it would take approximately 98–130 years for the stump and coarse root biomass (39.3 Mg C ha^{-1}) to fully decompose, had they been left in the stand. Therefore, the estimated 9 Mg C ha^{-1} of stump-root biomass retained in soil represents only a fraction of the temporal C pool potential. One has to acknowledge though, that the rate of decomposition of CWD is not a constant. The rate of C release (0.5–0.6 Mg C ha^{-1} yr^{-1}) from stump and coarse roots has been estimated to peak in the first 5–10 years following harvest (Grelle et al., 2012; Palviainen and Finér, 2015).

Considering that stumps can constitute up to 80% of the CWD in boreal whole-tree harvest clear-cuts and 28% of the CWD on the landscape level (Caruso et al., 2008; Bouget et al., 2012), stump removal inevitably results in a reduction of deadwood remaining in the stand (Eräjää et al., 2010; Anderson et al., 2015). Studies in Sweden have reported that the volume of low stump CWD on clear-cuts and young managed forests can be 2.5–4 times greater than other types of CWD (logs, branches, snags) (Caruso et al., 2008; Hjältén et al., 2010).

As highlighted by Walmsley and Goldbold (2009) the stump and coarse root system is often poorly defined, but the definition is nevertheless important in practical forestry (Hakkila and Parikka, 2002). Furthermore, defining where the stump ends and coarse roots begin, can be challenging as the dimensions of stump can be complex and highly variable. The current stump harvesting method involves an excavator, specifically equipped to break and split the stump and coarse roots prior to pulling them, as to avoid excess removal of roots (Laitila et al., 2008).

Finally, in contrast to the Finnish forest management guidelines, in which 30% of stumps (25–50 stumps ha^{-1} depending on the soil type) are advised to be left on site following stump harvesting (Äijälä et al., 2010) only 20% was left on site in our study. Nevertheless, this study provides valuable and novel insight into the biomass pools of the stump-root systems in Finnish Norway spruce stands.

5. Conclusions

In conclusion, the findings of this study indicate that (i) stump harvesting combined with site preparation tends to cause more extensive soil surface disturbance than site preparation alone, (ii) the soil surface disturbance is still noticeable 13 years after harvesting thus implying that the mixing effect of stump harvesting persist on soil surface, (iii) coarse roots and fine coarse roots represent a significant portion of the belowground biomass (73%) (iv) bark is a significant pool of nitrogen both in the stem and in the stump-root system (v) removing stump-root systems inevitably reduces coarse woody debris remaining in the stand (vi) stumps and coarse roots represent a large biomass (i.e. biofuel) component in the stand but utilizing stumps-root systems will result in carbon losses from the stand.

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